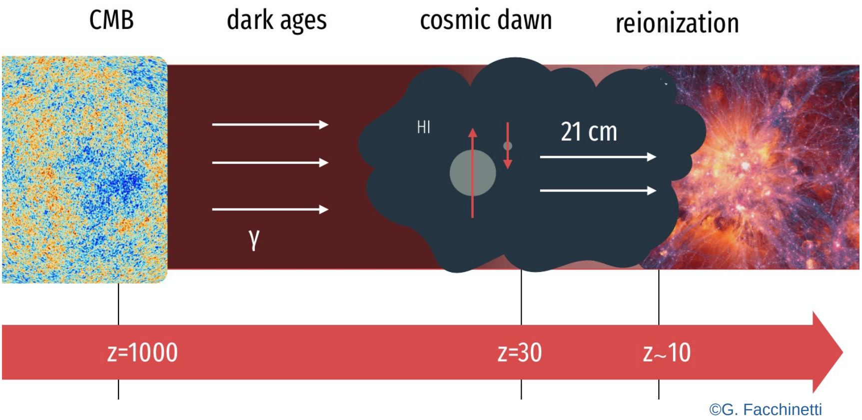
Cosmology Constraints on Dark Matter Decays

Laura Lopez Honorez

mainly based on JCAP 01 (2024) 005
with G. Facchinetti, Y. Qin and A. Mesinger

2024 International Workshop on Baryon and Lepton Number Violation
8-11/10/24

Cosmology Probes of DM decays



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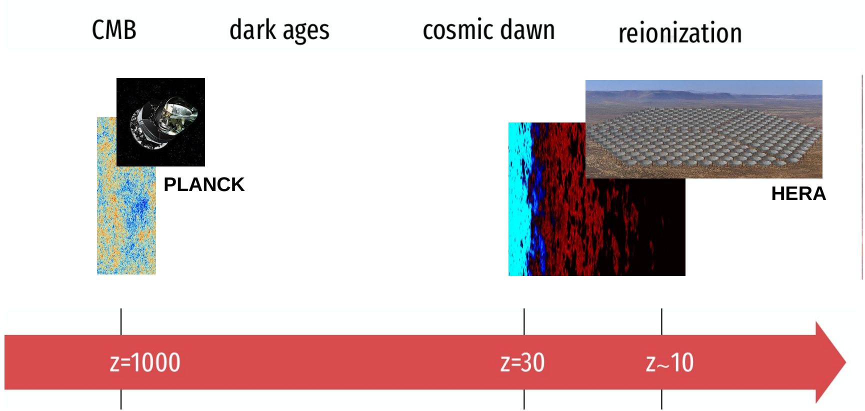

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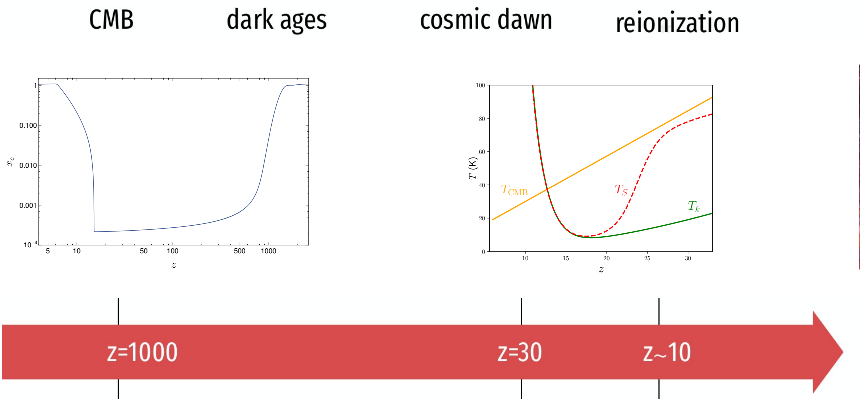

DM energy injection/deposition in early universe

see previous work e.g. [Adams'98,Chen'03, Hansen'03, Pierpaoli'03, Padmanabhan'05, Slatyer'15, Liu'19] for CMB, [Shchekinov'06, Furlanetto'06, Valdes'07, Chuzhoy'07, Cumberbatch'08, Natarajan'09, Yuan'09, Valdes'12, Evoli'14,LLH'16] for 21cm

- DM particles can decay into:
  - f, γ, W, Z, ... injected $\rightsquigarrow e^+, e^-, \gamma$
  - neutrinos $\rightsquigarrow$ suppressed depos. but possible via EW corrections

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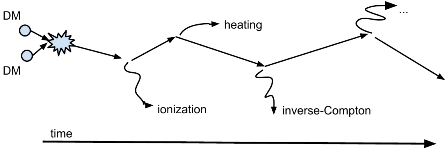
  - neutrinos $\rightsquigarrow$ suppressed depos. but possible via EW corrections
- Effectively DM deposit energy in the early Universe



[image from A. Vincent]

Rate of energy injection/deposition into c = heat, ionization, excitation

$$\left(\frac{dE_c(\mathbf{x},z)}{dtdV}\right)_{\text{deposited}} \equiv f_c(z) \left(\frac{dE(\mathbf{x},z)}{dtdV}\right)_{\text{injected}} \equiv f_c(z) \times \frac{\rho_{DM}}{\tau_{DM}} e^{-t/\tau_{DM}} .$$

$f_c(z)$ = energy deposition efficiency per channel
(can be obtained using `DarkHistory` [Liu '19, Liu'23])

Decaying DM $\equiv$ "Late" energy injection

Late energy inj. for decaying DM (w.r.t. annihilating vanilla WIMP):

$$\frac{dE_{\rm inj/b}}{dz} \propto \frac{\rho_{\rm DM}}{n_b(1+z)H}\frac{1}{\tau_{\rm DM}}$$

focus on $\tau_{\rm DM} > t_u$

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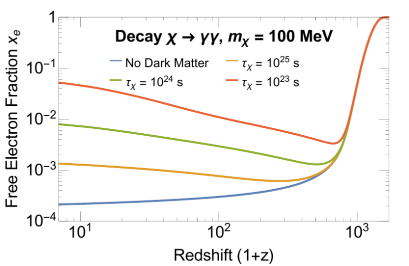
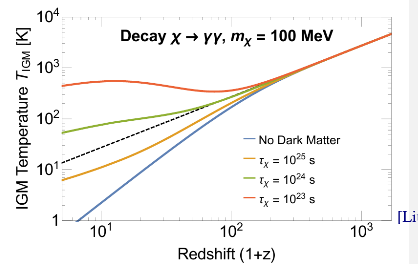


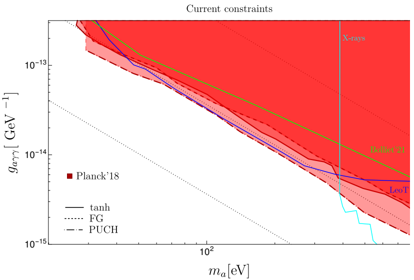


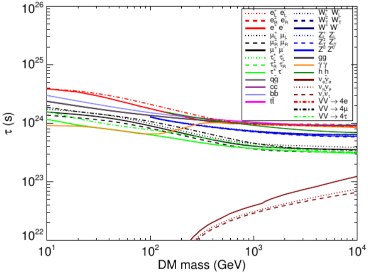
[Liu'16]

focus on $\tau_{\rm DM} > t_u$

CMB constraints on DM decay

see also [LLH'13, Liu'16, Slatyer'16,Capozzi'23, Liu'23, Xu'24, etc]



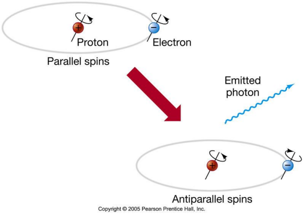


- CMB data most sensitive to decaying DM energy injections at $z \simeq 300$ [Slatyer'16].
- CMB bounds: $\tau_{\rm DM} >$ few $\times 10^{24}$ s at 95% CL [Slatyer'16]. Usually weaker than indirect DM searches probing up to $\tau \sim 10^{27-30}$s.
- Stronger sensitivity for MeV-GeV DM decaying to e^+e^- and <MeV DM decaying to $\gamma\gamma$ reaching $\tau_{\rm DM} \sim 10^{26}$ s at 95% CL see [Capozzi'23, Liu'23, Xu'24].

21cm Cosmology : near future late time probe

Cosmic Dawn and 21 cm signal

The Cosmic Dawn $\equiv$ period where first galaxies started to shine up until reionization (EoR). The most powerful probe is 21 cm spin flip line of HI :



- Transitions between the two ground state energy levels of neutral hydrogen HI $\rightsquigarrow$ 21 cm photon ($\nu_0 = 1420$ MHz)

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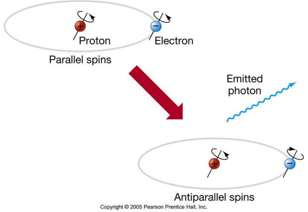
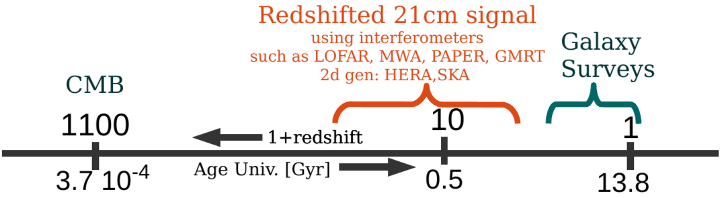
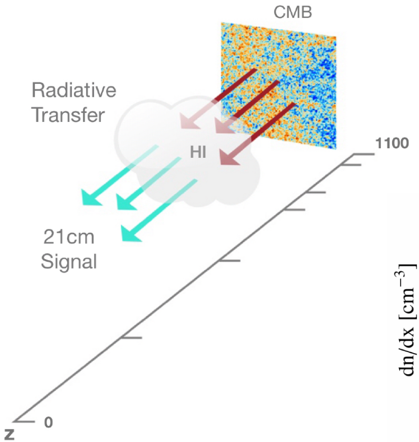


- Transitions between the two ground state energy levels of neutral hydrogen HI $\rightsquigarrow$ 21 cm photon ($\nu_0 = 1420$ MHz)
- 21 cm photon from HI clouds during Cosmic Dawn & EoR redshifted to $\nu \sim 100$ MHz $\rightsquigarrow$ new cosmology probe

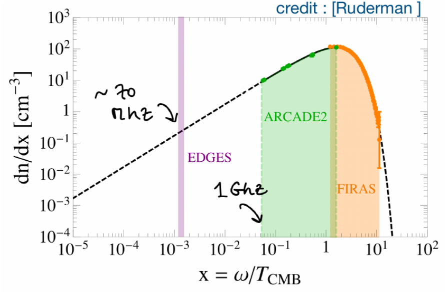


21 cm in practice



credit : [Kovetz]

- 21cm signal observed as CMB spectral distortions



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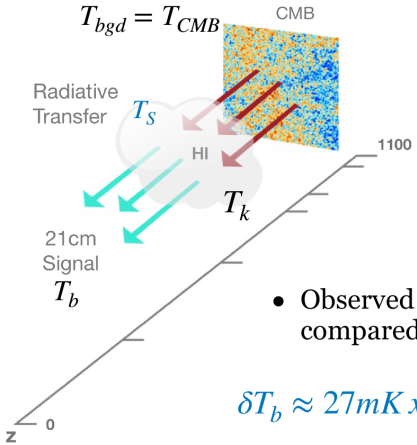


credit : [Kovetz]

- 21cm signal observed as CMB spectral distortions
- The spin temperature (= excitation T of HI) charaterises the relative occupancy of HI gnd state

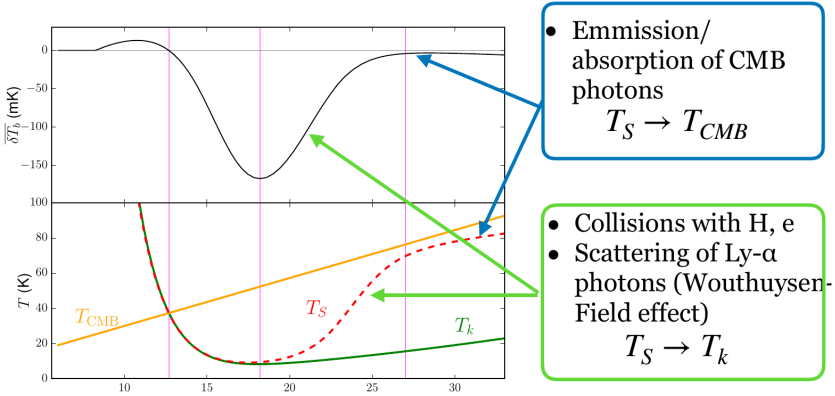
$$n_1/n_0 = 3\exp(-h\nu_0/k_B T_S)$$

- Observed brightness of a patch of HI compared to CMB at $\nu = \nu_0/(1+z)$

$$\delta T_b \approx 27mK\, x_{HI}(1+\delta)\sqrt{\frac{1+z}{10}}\left(1 - \frac{T_{CMB}}{T_S}\right)$$

The spin temperature

$$T_S^{-1} = \frac{T_{CMB}^{-1} + x_c T_k^{-1} + x_\alpha T_c^{-1}}{1 + x_c + x_\alpha}$$



$T(K)$ and δT_b obtained using `21cm Fast` [Mesinger'10]

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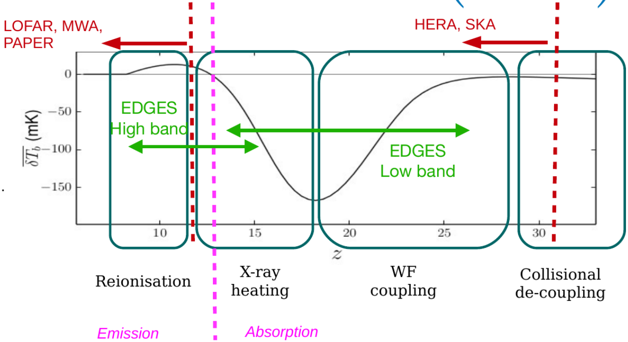

δT_b and Δ_{21} obtained using `21cm Fast` [Mesinger'10]

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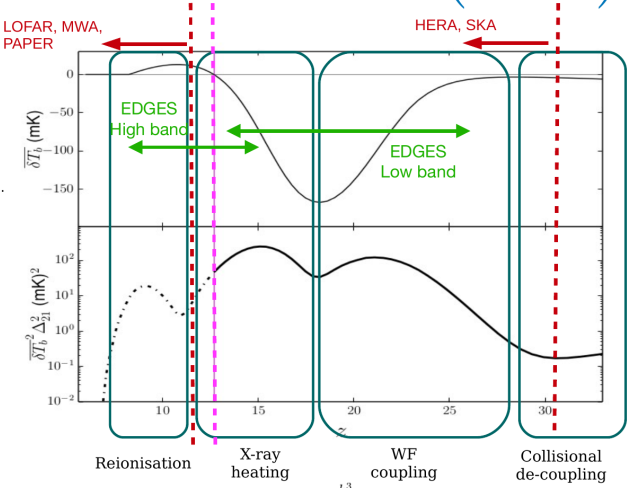
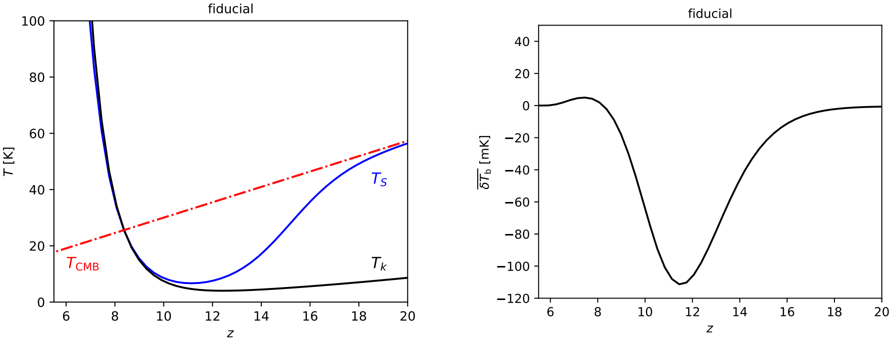


$$\langle \tilde{\delta}_{21}(\mathbf{k}, z)\tilde{\delta}^*_{21}(\mathbf{k}', z)\rangle \equiv (2\pi)^3\delta^D(\mathbf{k}-\mathbf{k}')P_{21}(k,z) \qquad \Delta^2_{21}(k,z) = \frac{k^3}{2\pi^2}P_{21}(k,z)$$

δT_b and Δ_{21} obtained using `21cm Fast` [Mesinger'10]

Decaying DM and 21cm power spectrum

Impact of decaying DM on T_k and δT_b



plots made using exo21cmFast developped by G. Facchinetti merging 21cmFast and DarkHistory

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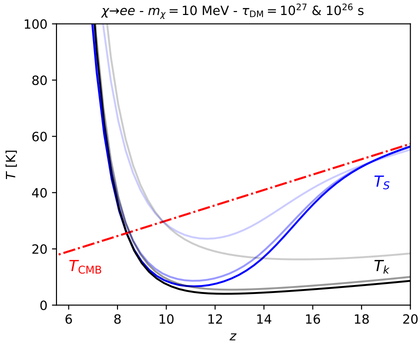

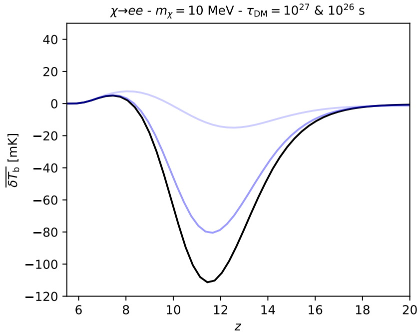

DM energy injection implies

- new source of heating, earlier than X-rays from stars
- suppressed absorption in δT_b

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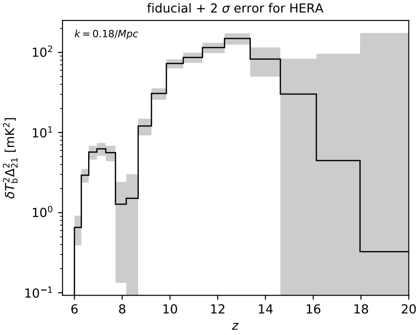
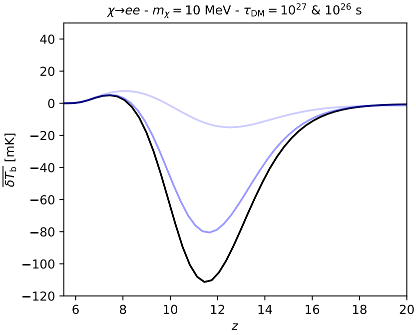
Impact of decaying DM on δT_b and Δ_{21}





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$k = 0.18$/Mpc is relatively free from foregrounds.

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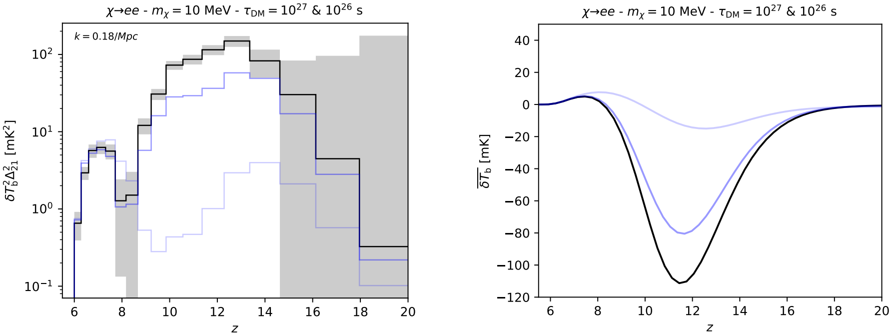

- 2 σ error bands from 21cmSense for HERA.
- DM decays give suppressed power around X-ray heating - Lyman-α coupling time
- Lifetimes as large as $\tau_{DM} = 10^{27}$ s shall leave a measurable imprint

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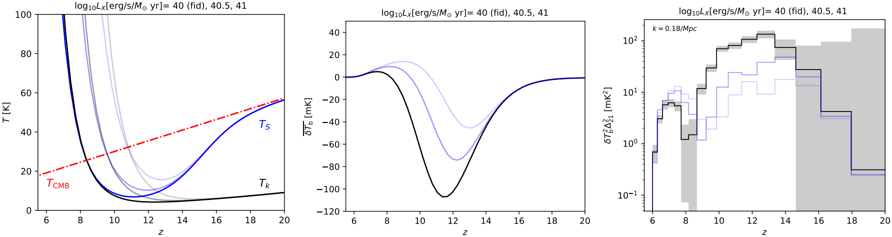
Degeneracies with astro parameters

For example, X-ray heating from stars parametrized with a normalisation of soft-band X-ray luminosity per unit SFR: $L_X \sim 10^{40}$ [erg/s/$M_\odot$ yr].



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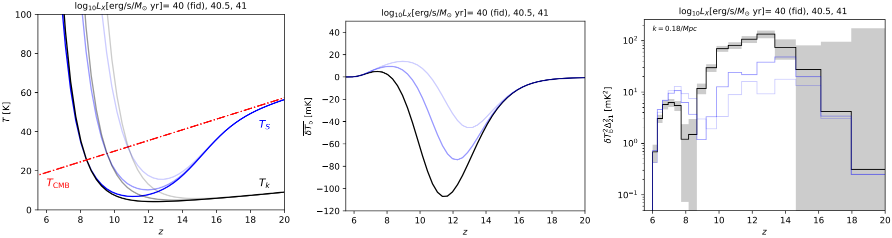
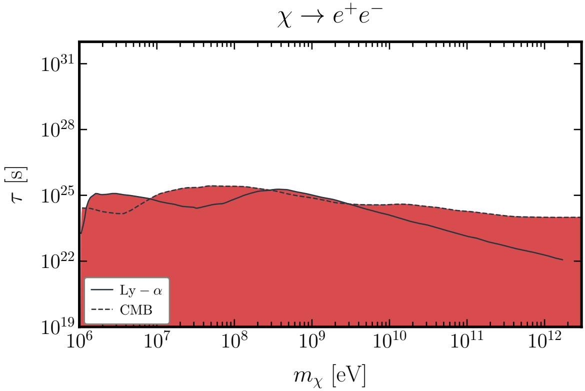


- Increasing L_X also gives rise to a suppression of the PS at large z
- X-rays drive an 21cm signal saturated earlier $\rightsquigarrow$ stronger contrast at low z.

It is possible to disentangle L_X effect from τ_{DM}

plots with exo21cmFast developped by G. Facchinetti merging 21cmFast and DarkHistory

Forecasts of 21cm bounds on $\chi \to ee$



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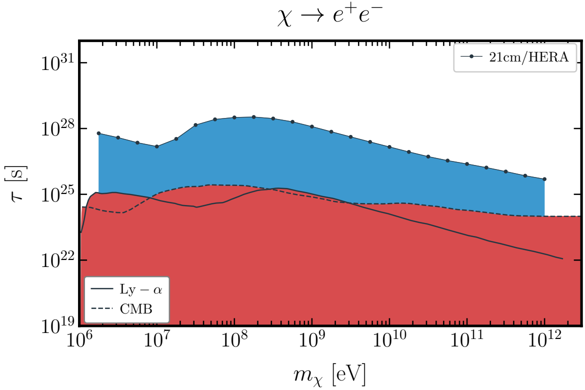

- (optimistic) Fisher Matrix forecasts for HERA 331 antennas and $t_{obs} = 1000$ h
- $\tau_{\rm DM} \gtrsim 10^{27-28}$s

- Future redhifted 21cm signal power-spectrum measurements can surpass current CMB and/or Lyman-α sensitivity by 2-3 orders of magnitude.

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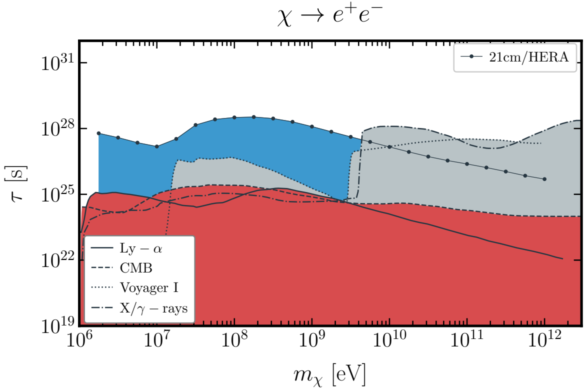

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- Can put more stringent bounds than indirect DM searches bounds...

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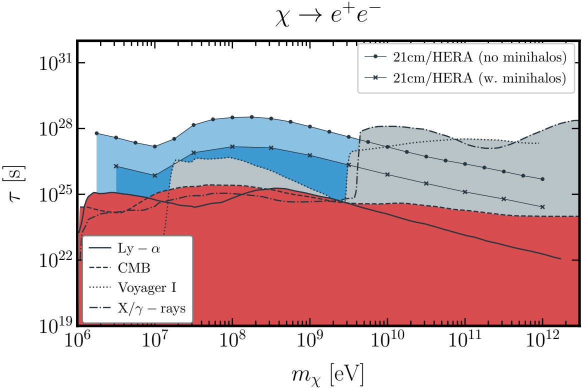

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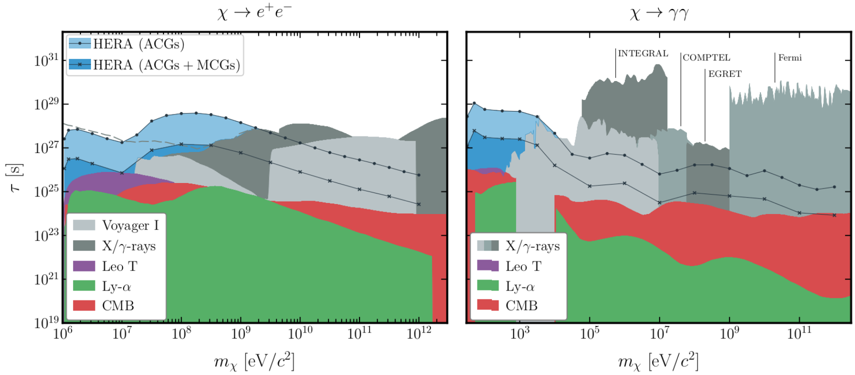
- Can put more stringent bounds than indirect DM searches bounds...
- ...even when considering an early second population of stars (POPIII)

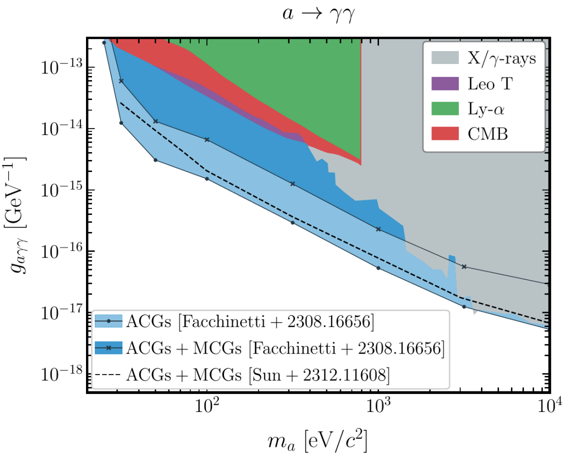
Forecast of 21cm bounds on $\chi \to ee$ & $\gamma\gamma$



updated constraints [Facchinetti et al'24] using HERA.

Depending on the assumed galactic magnetic fields ($v_A = 13.4$ km/s for the dashed gray line) reacceleration of secondary CR can give rise to competitive limits w/ XMM-Newton for e^+e^- see [De la Torre Luque'24]

Application to ALPs $a \to \gamma\gamma$

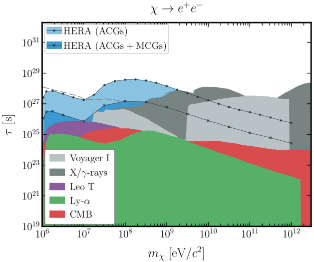


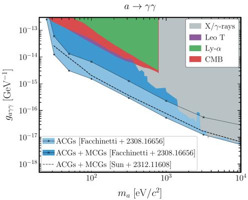
21cm observations shall improve CMB constraints in the ALP coupling to photons by up to ~ 2 orders of magnitude for $m_a \sim 10 - 10^3$ eV.

Conclusions

Dark matter energy injection through decays imply rather late time (later than WIMP) enhancement of ionization and IGM temperature.
Low z data such as 21cm power spectrum measurements might become a key probe for decaying DM

- We forecast HERA sensitivity with 331 antennas under deployment in South Africa and taking data.
- Expected to surpass CMB/ Lyman-α sensitivity and reach $\tau_{DM} > 10^{27-28}$ s.
- DM annihilation is the next step, checking the impact of the $B(z)$.



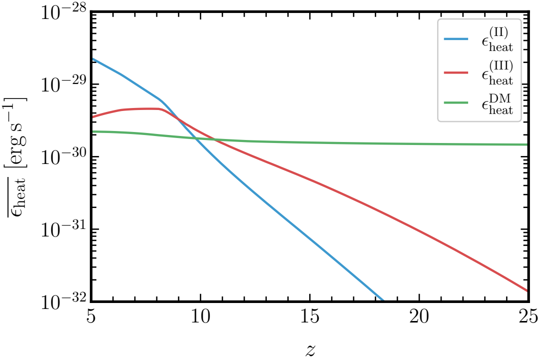


NB: we have implemented homogeneous energy injection. Inhomogeneous injection was studied in details by [Sun'23]. Similar sensitivity prospects! But δT_b can differ.

Thank you for your attention!!

Backup

Rates of energy injection into heat



- DM heats the IGM well before POPII stars but is less efficient at low z
- POPIII stars give rise to heating rate “more similar” to DM than POPII.

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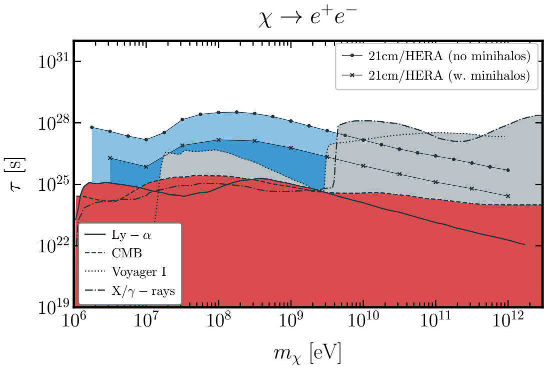

- DM heats the IGM well before POPII stars but is less efficient at low z
- POPIII stars give rise to heating rate “more similar” to DM than POPII.

Stronger degeneracy with POPIII star heating parameters
$\rightsquigarrow$ less stringent constraints on DM decay width
when POPIII stars are taken into account.

Decaying DM = Later energy injection

Early energy inj. for s-wave ann. DM (aka WIMP):

$$\frac{dE_{\rm inj/b}}{dz} \propto \frac{\rho_{\rm DM}^2}{n_b(1+z)H}\frac{\sigma v_0}{m_{\rm DM}}$$
$$\propto (1+z)^{1/2}\frac{\sigma v_0}{m_{\rm DM}}$$

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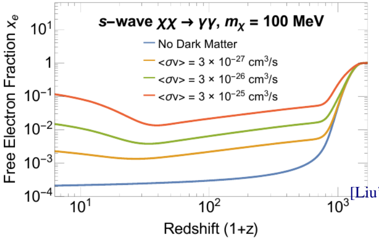

[Liu'16]

+ later Boost $\sim B(z)$ of $\bar{\rho}_\chi^2$ from structure formation see e.g. [LLH'13, Liu'16, etc]

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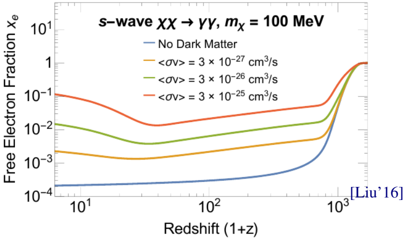
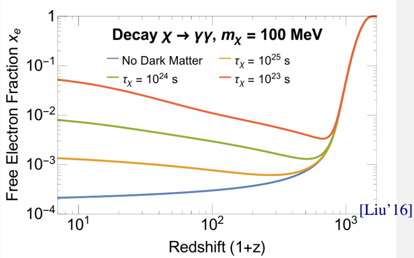


+ later Boost $\sim B(z)$ of $\bar{\rho}^2_\chi$ from structure formation see e.g. [LLH'13, Liu'16, etc]

Late energy inj. for decaying DM (beyond WIMP):

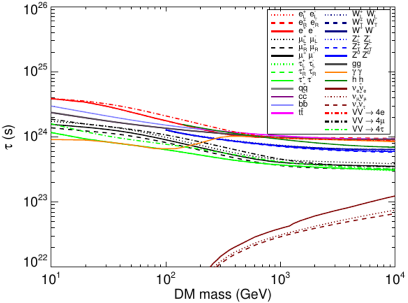
$$\frac{dE_{\rm inj/b}}{dz} \propto \frac{\rho_{\rm DM}}{n_b(1+z)H}\frac{1}{\tau_{\rm DM}}$$
$$\propto (1+z)^{-5/2}\frac{1}{\tau_{\rm DM}}$$



focus on $\tau_{\rm DM} > t_u$

Existing CMB constraints on DM decay

see also [LLH'13, Liu'16, Slatyer'16,Capozzi'23,...]



$\rightsquigarrow$ $\tau_{\rm DM} \gtrsim$ few $\times\ 10^{24}$ s at 95% CL [Slatyer'16]

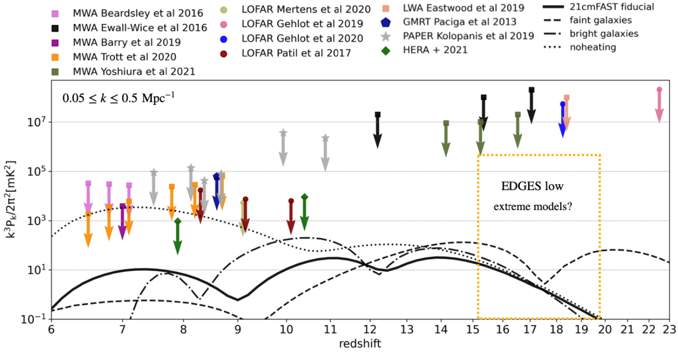
see also [Liu'20] w/ Ly-α and see [Capozzi'23 & Liu'20]: $\tau_{\rm DM} \gtrsim$ few $\times\ 10^{26}$s for m_χ < keV w/ CMB

Cosmo bounds are usually weaker than indirect DM searches

probing up to $\tau \sim 10^{27-30}$s

except for MeV-GeV DM decaying to e^+e^- and <MeV DM decaying to $\gamma\gamma$.

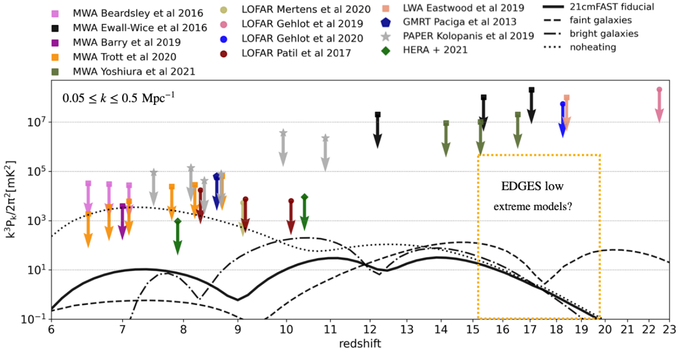
Constraints on 21cm Power spectrum?



[Shimabukuro'23]

- We will consider HERA interferometer in South Africa with 331 antenas (14m dishes) under deployment (=SKA precursor).
- First data from HERA phase I probed $z \sim 8 - 10$ with only ~ 70 ant. already set a lower bound on X-ray heating [HERA'21& 22]. Actually the full set of 331 antennas is already build and soon taking data.

Constraints on 21cm Power spectrum?

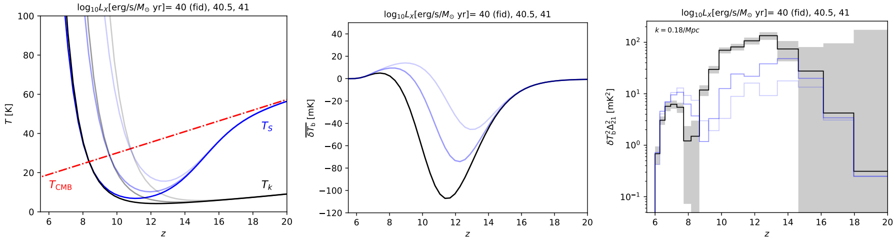


[Shimabukuro'23]

- We will consider HERA interferometer in South Africa with 331 antenas (14m dishes) under deployment (=SKA precursor).
- First data from HERA phase I probed $z \sim 8 - 10$ with only ~ 70 ant. already set a lower bound on X-ray heating [HERA'21& 22]. Actually the full set of 331 antennas is already build and soon taking data.

Degeneracies with astro parameters

For example, X-ray heating from stars parametrized with a normalisation of soft-band X-ray luminosity per unit SFR: $L_X \sim 10^{40}$ [erg/s/$M_\odot$ yr].



plots with exo21cmFast developped by G. Facchinetti merging 21cmFast and DarkHistory

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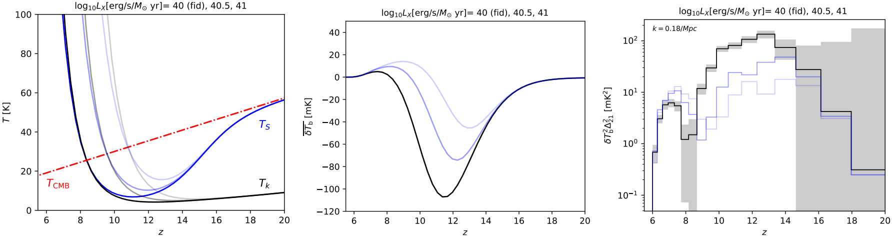
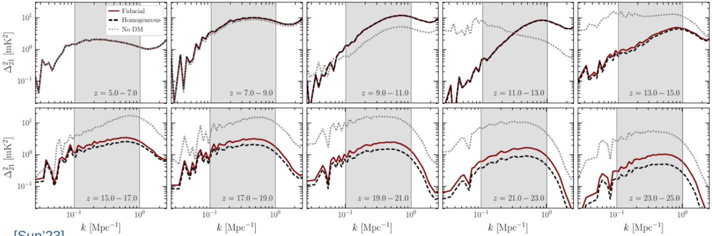


- Increasing L_X also gives rise to a suppression of the PS at large z
- X-rays from stars drive a 21cm signal saturated earlier
  $\rightsquigarrow$ stronger contrast at low z.

It is possible to disentangle L_X effect from τ_{DM}

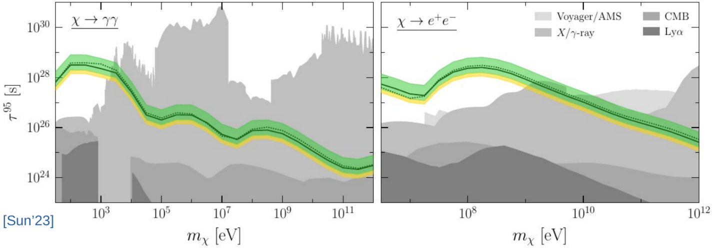
plots with exo21cmFast developped by G. Facchinetti merging 21cmFast and DarkHistory



[Sun'23]

Figure 6. **Example T_{21} lightcone power spectra under DM decaying to photons.** The lightcone power spectra computed for redshifts between $z = 5$ and $z = 25$ for the scenario of DM decay to photons for $m_\chi = 5\,\mathrm{keV}$ and $\tau = 10^{25}\,\mathrm{s}$.

- [Sun'23] studied spatially inhomogeneous energy injection and deposition during cosmic dawn.
- larger fluctuations on small scales in the inhomogeneous treatment than in the homogenized one.

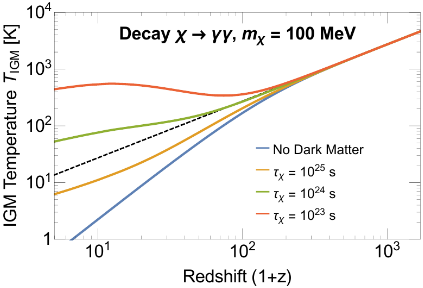


[Sun'23]

- [Sun'23] studied spatially inhomogeneous energy injection and deposition during cosmic dawn.
- larger fluctuations on small scales in the inhomogeneous treatment than in the homogenized one.
- Projected sensitivities calculated with the (in-)homogenized treatment are not appreciably different. Due to both DM and stellar reio track $\delta_m \rightsquigarrow$ more degeneracies DM-astro in the inhomogeneous case.

DM energy injection implies earlier heating

DM decays heats the IGM before astro sources light-on.



[Liu'16]

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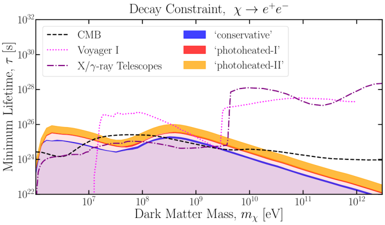

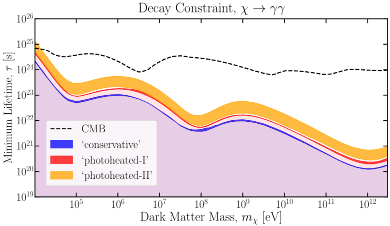

[Liu'20]

The IGM temperature T_k can be probed at low z by using:

- Lyman-α forest data at $2 \lesssim z \lesssim 6$ with $T_k \sim 10^4$ K [Liu'20,Capozzi'23]

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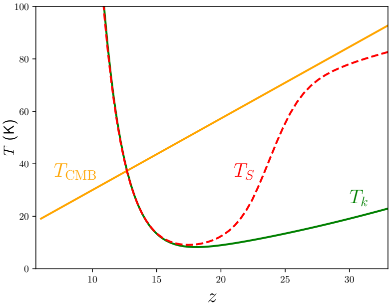
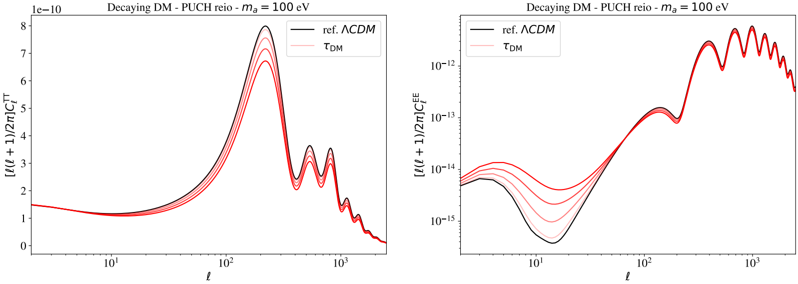


The IGM temperature T_k can be probed at low z by using:

- Lyman-α forest data at $2 \lesssim z \lesssim 6$ with $T_k \sim 10^4$ K [Liu'20,Capozzi'23]
- Redshifted 21cm signal detected by radio telescope arrays that will measure $|\Delta_{21}(k,z)|^2$ at $z \subset [6,25]$ with $T_k \sim 10$ K [Furlaneto'06, Evoli'14, Liu'18]

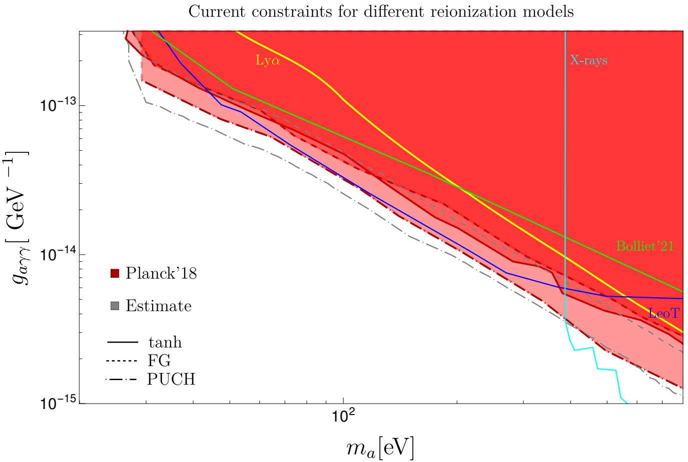
DM Decay imprint on CMB anisotropy spectra



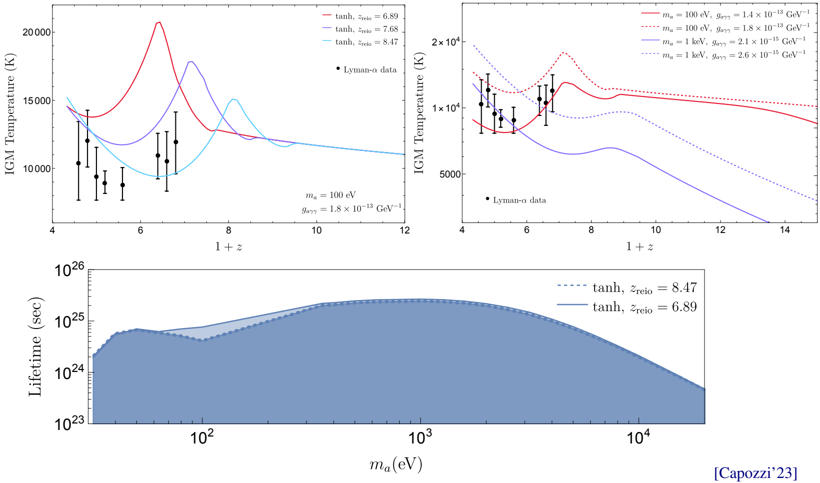
- increased residual ionization after recombination (steadily growing with time)
- increased the optical depth to reionization $\tau_{\rm reio} = \int dt\, x_e n_b \sigma_T$
- attenuates correlations at small scales (large ℓ) and enhances low-ℓ polarisation power.

The low-ℓ data are important to discriminate energy injection from other cosmo params such as n_s, A_s affecting the amplitude of the CMB peaks.

$a \to \gamma\gamma$

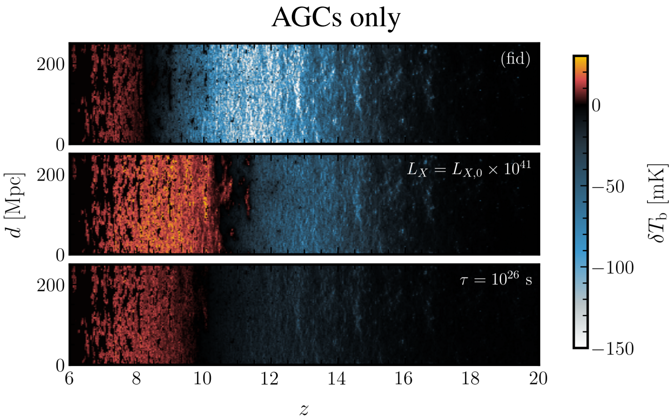


T_k for $a \to \gamma\gamma$



[Capozzi'23]

DM decay and earlier heating



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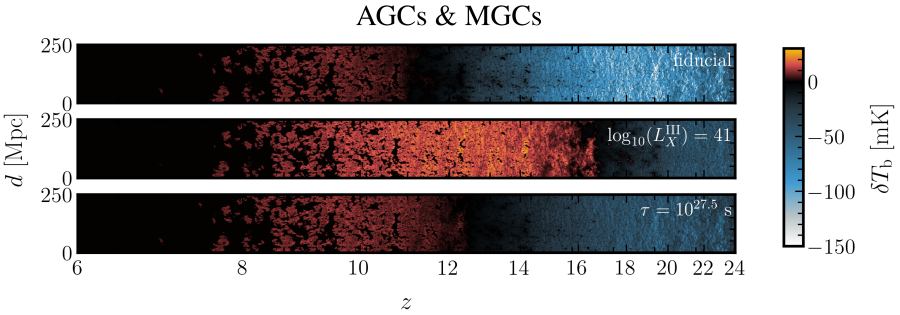
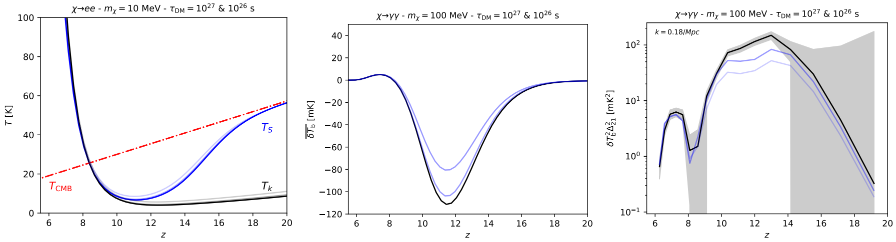


Impact of DM$\to\gamma\gamma$ on T_k, δT_b and Δ_{21}



DM energy injection implies

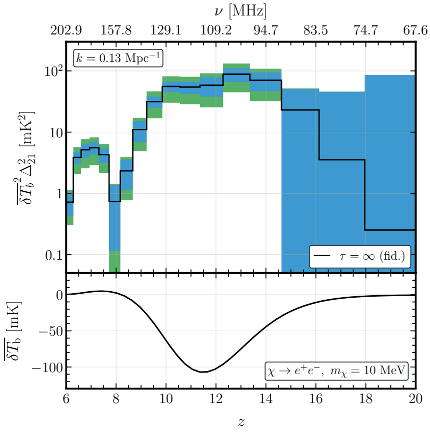
- new source of heating, earlier than X-rays from stars
- suppressed absorption in δT_b
- suppressed power at large z

plots made using exo21cmFast developped by G. Facchinetti merging 21cmFast and DarkHistory

Fisher matrix analysis

- Fisher matrix can be used to estimate the minimum uncertainties of parameters given observations $\sigma_{Fish} \lesssim \sigma_{true}$ [Albrecht et al. 2009] (= optimistic estimate of the errors) (e.g. using 21cmFish by C. Mason'22, they show that $\sigma_{Fish,i}$ are within 40% of the those obstained with MCMC for ΛCDM)
- The Fisher formalism assumes that the likelihood is Gaus- sian within the parameter range under consideration and $F_{ij} = \sum_{k,z} \frac{\partial \Delta_{21}}{\partial \theta_i} \frac{\partial \Delta_{21}}{\partial \theta_j} (\sigma^2_\Delta(k,z))^{-1}$ where σ^2_Δ measurement error in Δ_{21} at a given k, z bin. Forecasted uncertainty in the i-th parameter is $\sigma(\theta_i) = \sqrt{\mathcal{C}_{ii}}$ where the covariance matrix $\mathcal{C} = F^{-1}$.
- $\sigma^2_\Delta(k,z)$ is obtained w/ 21cmSense considering HERA thermal noise plus the cosmic variance plus 20% 'modelling uncertainty'. The noise assumes 1000 hours of obs. ($\sim$ 167 days for 6h/day with max 180 effective days of obs/year) using 331 antennae.
- foregrounds are taken into account by putting a cut neglecting $k_\parallel < 0.1/Mpc$
- boxes have a comoving volume of $(250Mpc)^3$ on a grid of $z = 6 - 30$ ($\sim \nu = 50 - 250$ Mhz). We use $BW = \Delta\nu_{\max} = 8$ Mhz which sets $k_{\parallel,min}$ at a given z. Notice that given HERA config, the available $k_\parallel > k_\perp$.

DM vs X rays with POPII stars only



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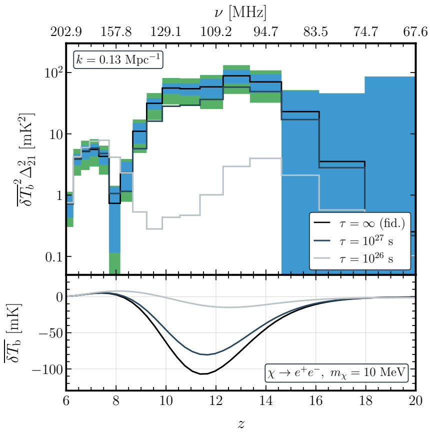

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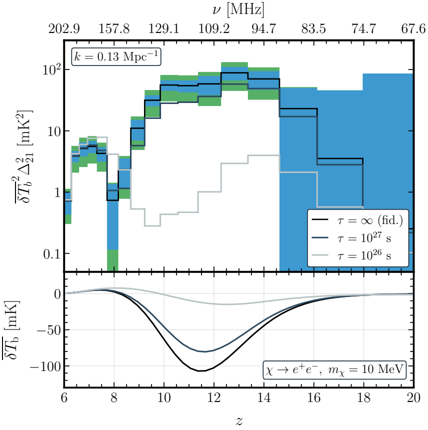
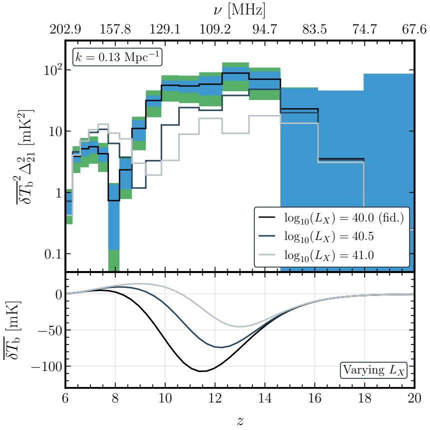
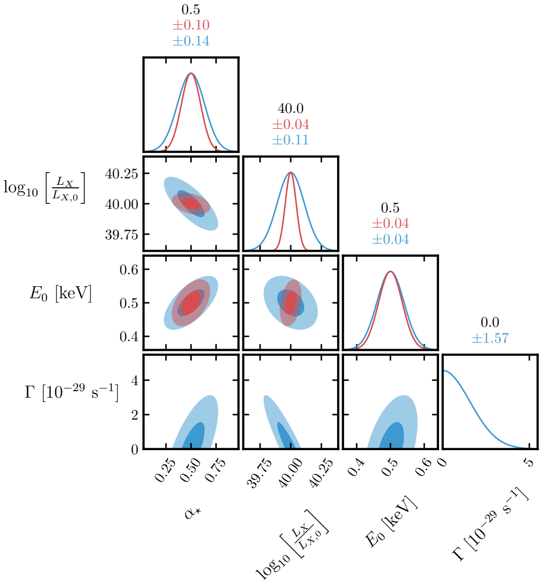


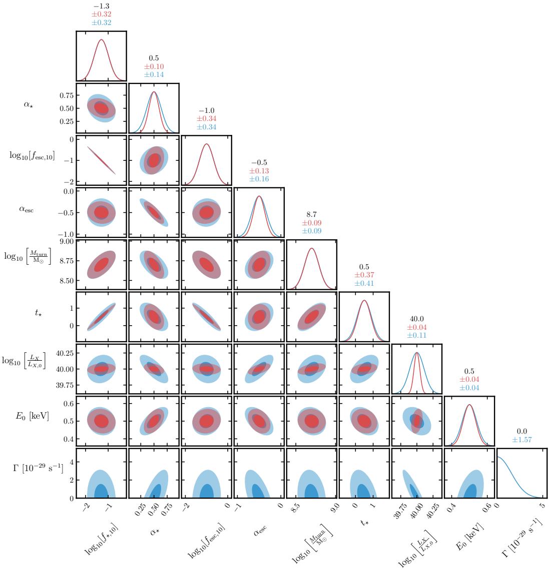


21cm Fisher results for $\chi \to ee\ m_\chi = 100$ MeV



- L_X normalisation of soft-band X- ray (< 2 keV which efficiently heat IGM) luminosity per unit SFR. E_0 minimum in X-ray energies which can escape galaxies.
- stellar mass (M_*) to halo mass ratio is described by a power law: $\alpha_*, f_{*,10}$ = low mass slope, normalisation for galaxies forming pop II stars

21cm Fisher results for $\chi \to ee$ $m_\chi = 100$ MeV



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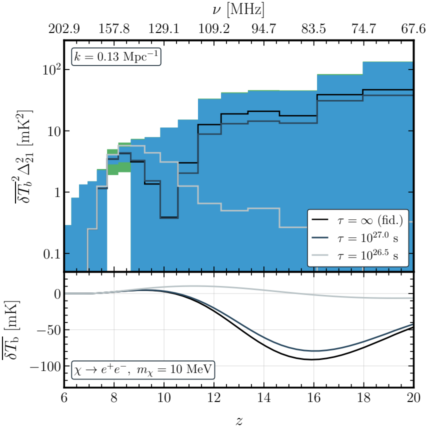
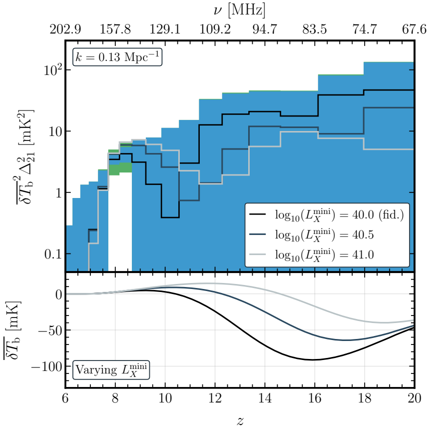
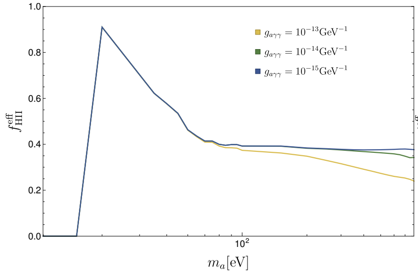
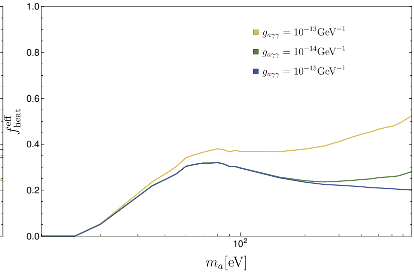
DM vs X rays with POPII&III stars only



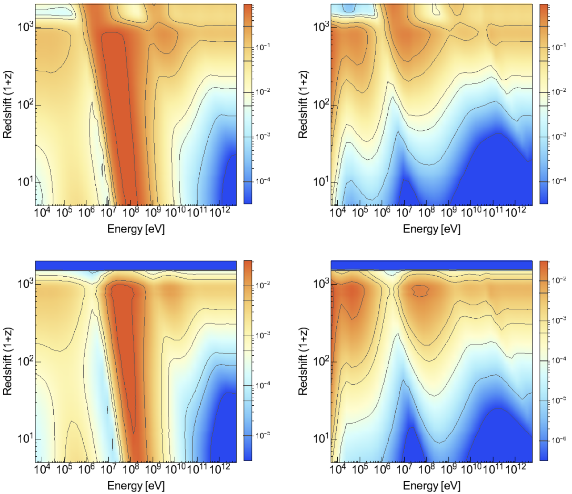


$f_{ionH,eff}$ & $f_{heat,eff}$ for $a \to \gamma\gamma$



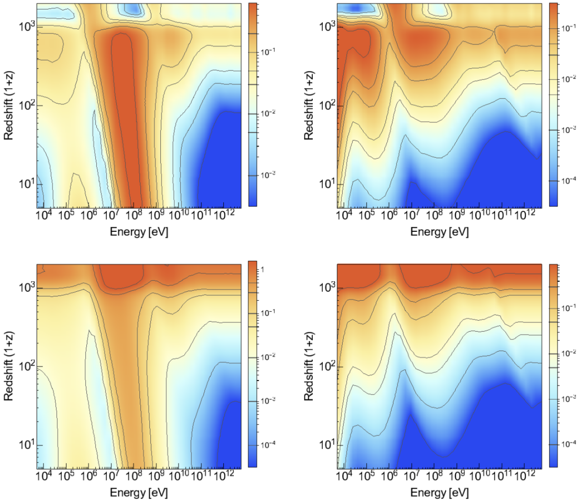


f_{ionH} & f_{ionHe} for $\chi \to ee,\ \gamma\gamma$



[Liu'16]

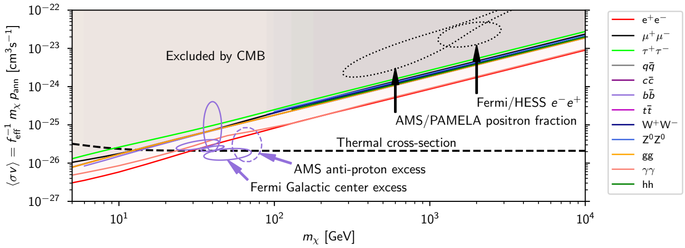
f_{exc}& f_{heat} for $\chi \to ee,\ \gamma\gamma$



[Liu'16]

CMB constraints on DM annihilation

see e.g. [Chen'03, Padmanabhan'05, Cirelli'09, Slatyer'09, Galli'11, Giesen'12, LLH'13, Galli'13, Madhavacheril'13, Poulin'15,...]

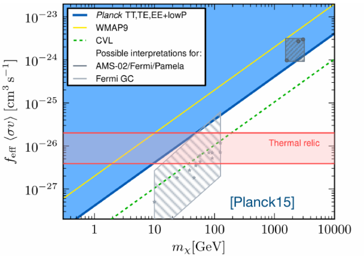


$\rightsquigarrow$ $p_{ann} = f_{eff}\langle\sigma v\rangle/m_{DM} < 3.2\,10^{-28}$ cm^3/s/GeV at 95% CL [Planck'18]

- CMB data most sensitive to annihilating DM energy injections at $z \simeq 600$ [Finkbeiner'12]. For annihilating DM, one can take $f_c(z) = f_{eff} = f_c(z = 600)$.
- Advantage of CMB compared to other DM annihilation probes: do not suffer astrophysics uncertainties (such as ρ_{DM}) and no contributions from halos for σv independent of v (s-wave annihilation) [LLH'13, Poulin'15, Hongwan'16].

DM annihilation and earlier heating

see also [Hansen'04, Pierpaoli'04, Bierman'06, Mapelli'06, Valdes'07, Natarajan'08, Evoli'14, etc]



see also [Valdes13, Evoli14, D'Amico18,Liu18]

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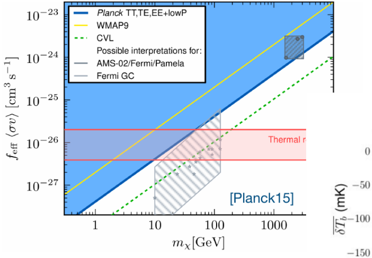
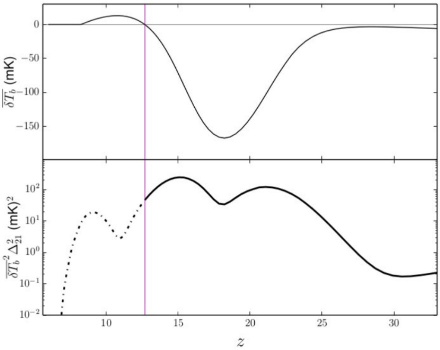


[LLH, Mena, Moline,Palomares,Vincent 16]



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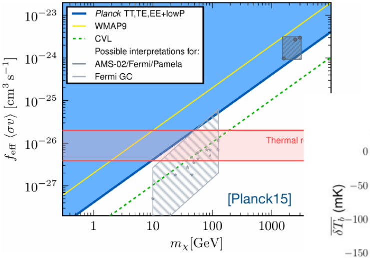

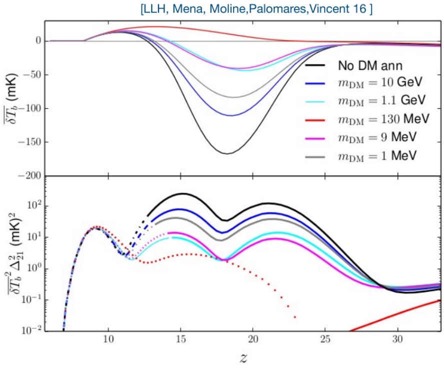

- Suppressed absorption
- Imposing some maximal δTb could constrain DM annihilation

see also [Valdes13, Evoli14, D'Amico18,Liu18]

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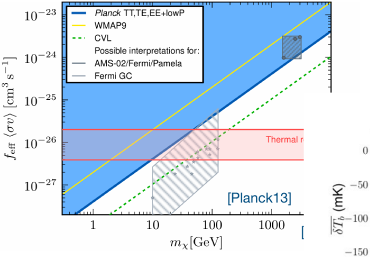
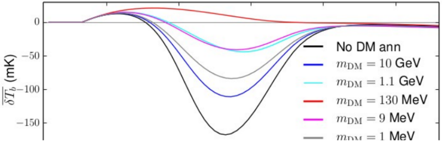
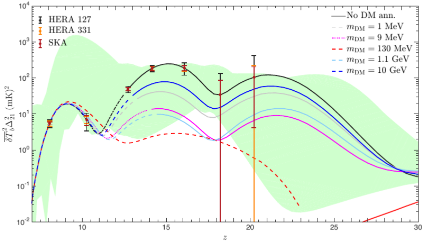


Beware!
large astrophysics
uncertainties

[LLH, Mena, Moline,Palomares,Vincent 13]





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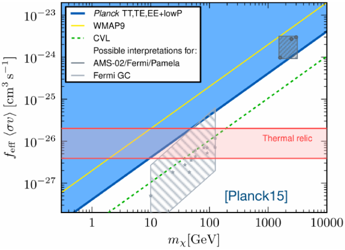

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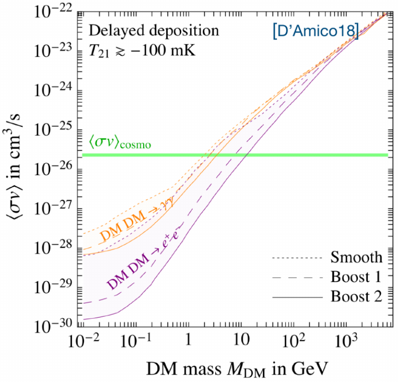
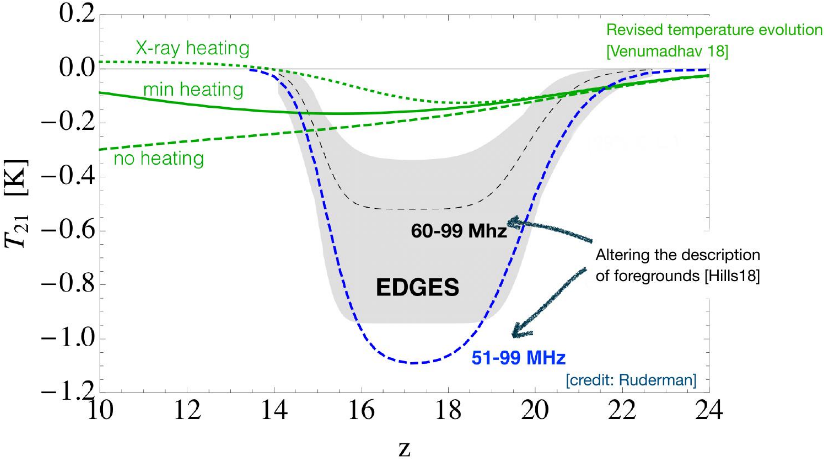


see also [Valdes13, Evoli14,LLH16, Liu18]

Constraints on 21cm Global signal?



Status 21cm Global signal

- [2112.06778] SARAS 3: The sensitivity of the SARAS 3 data rules out a cosmological origin for the profile found by Bowman et al. and suggests that the spectral distortions in the measured sky spectrum by the EDGES low-band instrument is dominantly instrument systematics.
- [2210.04910] HERA w/ 94 antennas: Since a radio background can also increase the amplitude of 21 cm fluctuations, limits from HERA can constrain astrophysical parameters describing models with excess radio background. In general, HERA excludes models with high radio background and low Xray flux, since they would produce the brightest amplitude of 21 cm fluctuations.
- [2212.00464] Bevins et al: The residuals observed in SARAS3 data, after modelling for foregrounds, do not provide evidence for a detected 21-cm signal, including the EDGES profile, and they allow for the first time constraints of astrophysics at cosmic dawn. For example, by conditioning the prior parameter space to be compatible with the EDGES detection and neglecting the steep walls of the feature, we find that $\sim 60\%$ of the available parameter space is still consistent with the SARAS3 data.

CMB analysis for $a \to \gamma\gamma$

Goals of our analyis:

- Up to date MCMC analysis using Planck'18 data with $f_{\rm eff} = f_c(z = 300)$.
  The few $\times$ 10 eV energy photons are very good at ionizing the medium!
  We modified CLASS to account for $f_{\rm eff} = f_c(z = 300, m_a, g_a)$ from DarkHistory.

- Check the impact of reionization history

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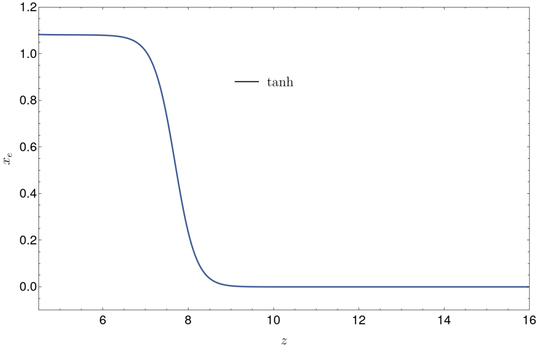
  - parametric $x_e^{\rm tanh}$

all shown reio agree with Planck'18:
$\tau_{\rm reio} = 0.054 \pm 0.007$



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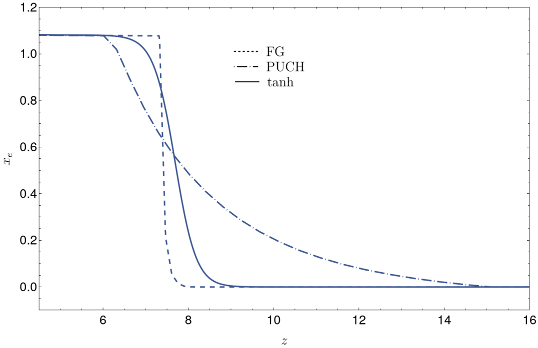

Without DM, PUCH reio model gives larger $\tau_{\rm reio} = \int dt\, x_e n_b \sigma_T$
$\rightsquigarrow$ Stronger CMB bounds for PUCH-like model expected

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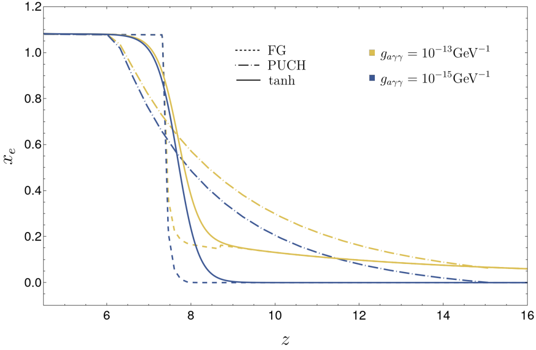

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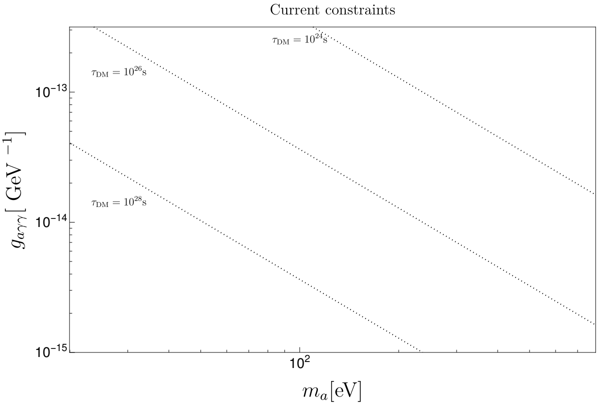
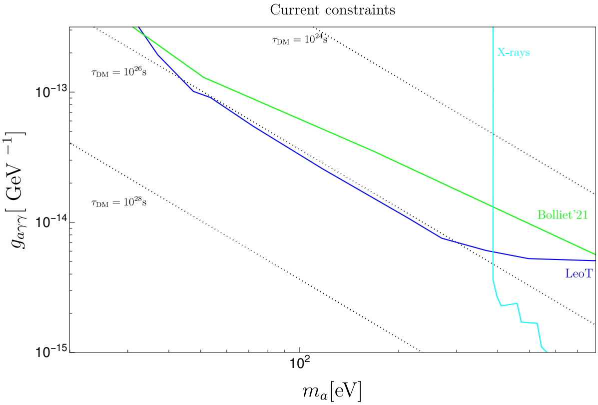
CMB bounds $a \to \gamma\gamma$



$$\tau_{DM}^{-1} = \frac{g_{a\gamma\gamma}^2}{64\pi} m_a^3$$

CMB bounds $a \to \gamma\gamma$



$$\tau_{DM}^{-1} = \frac{g_{a\gamma\gamma}^2}{64\pi} m_a^3$$

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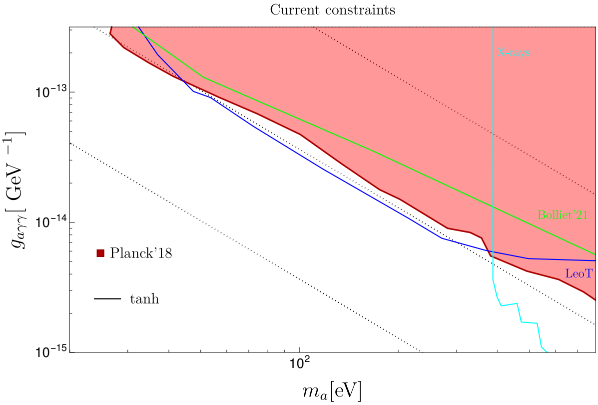

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- For $x_e^{\tanh}$, $z_{\rm reio}$ is marginalized over $z_{\rm reio} = [5, 13]$.
- $\tau_{\rm DM} \gtrsim 10^{26}$s

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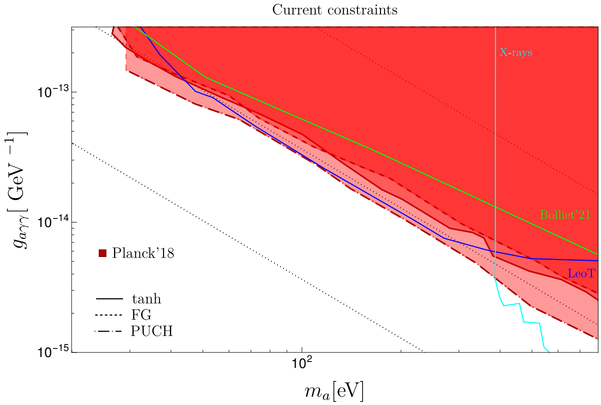

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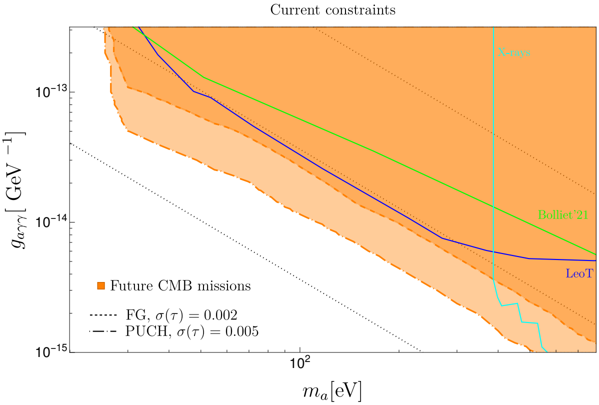

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- Currently, fixing $x_e(z)$ to a reionization history in agreement with Planck does not significantly change the bounds
- Future CMB variance limited Experiments will definitively give more stringent bounds. In the latter case, the reionization history from stars will matter.

bla

This is really the end